

# Simultaneous X-ray and radio mode switching: Local and/or magnetospheric phenomenon?

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Netherlands Institute for Space Research



UNIVERSITY OF AMSTERDAM

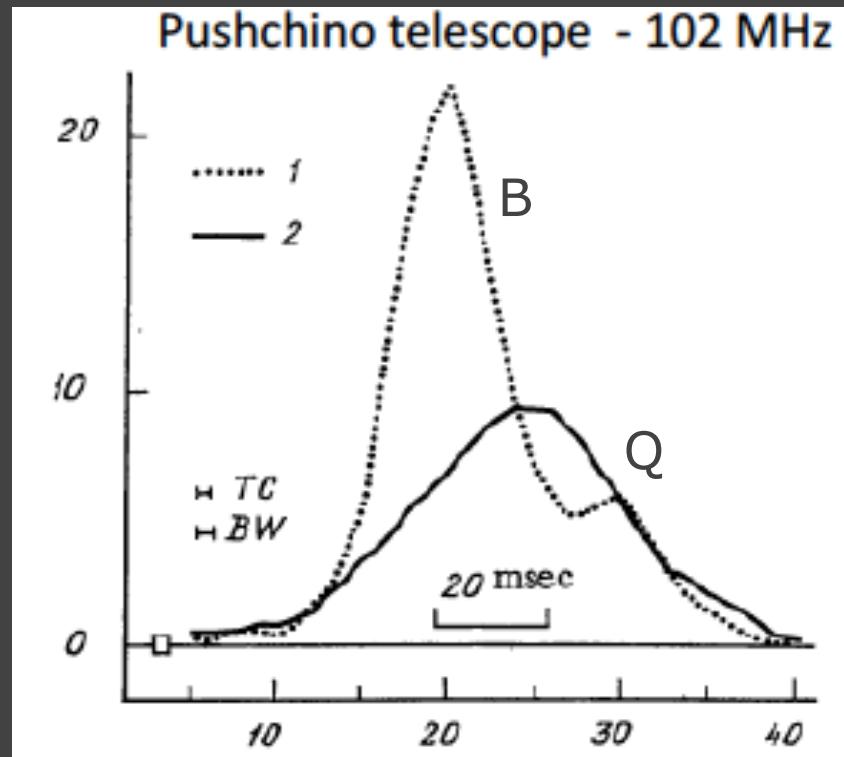
Netherlands Organisation for Scientific Research (NWO)

# Outline

- Radio-mode switching; PSR B0943+10, B1822-09, B0823+26
- Synchronous X-ray and radio-mode switching in PSR B0943+10.
  - Hermsen W., Hessels, J.W.T., Kuiper, L., van Leeuwen, J., Mitra, D. et al. (Science 2013)
  - Mereghetti S., Kuiper, L., Tiengo, A., Hessels, J., Hermsen, W. et al. (2016)
- Simultaneous X-ray and radio observations of the radio-mode-switching pulsar PSR B1822-09.
  - Hermsen, W., Kuiper, L., Hessels, J.W.T., Mitra, D., Rankin, J.M. et al (2017)
- Discovery of synchronous X-ray & Radio moding of PSR B0823+26.
  - Hermsen, W., Kuiper, L., Basu, R., Hessels, J.W.T., Mitra, D. et al. (2018), submitted to MNRAS
- Comparison results on PSRs B0943+10, B1822-09 & B0823+26

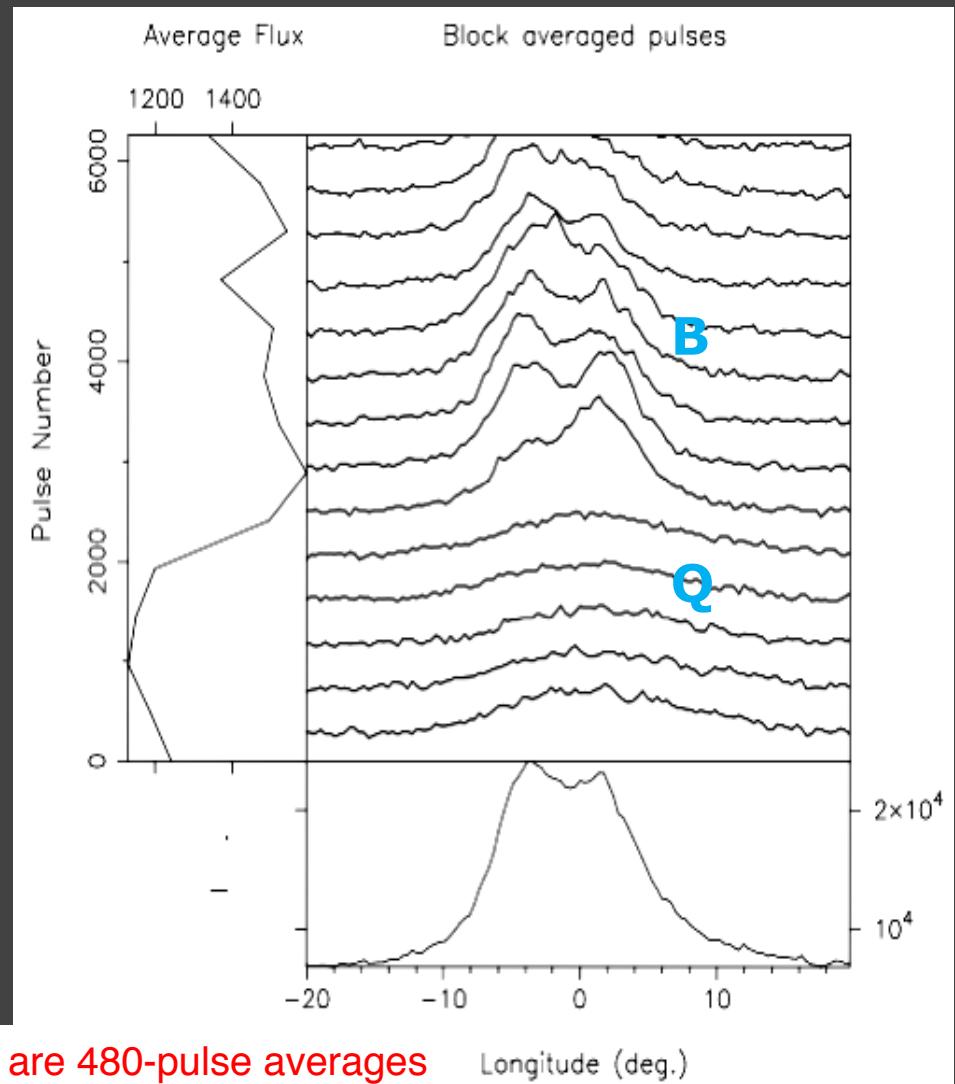
It began with a question in 2006.....

PSR B0943+10: radio-mode switching



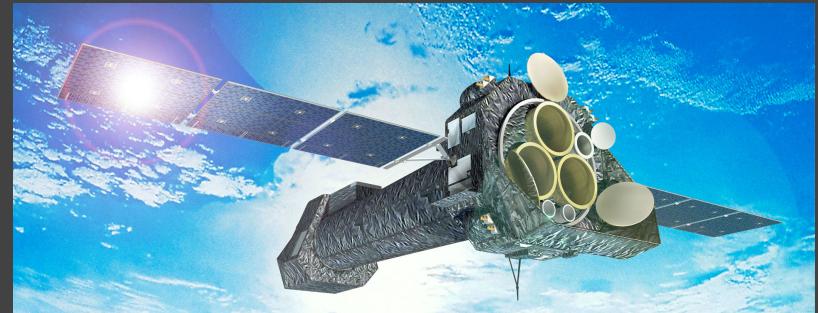
Suleymanova & Izvekova 1984

Q-to-B-Mode Transitions in B0943+10  
Arecibo 327-MHz observations in 2003



# Four radio-X-ray campaigns on three mode switching pulsars 2011 - 2017

X-rays: XMM



Radio:  
GMRT



LOFAR



WSRT



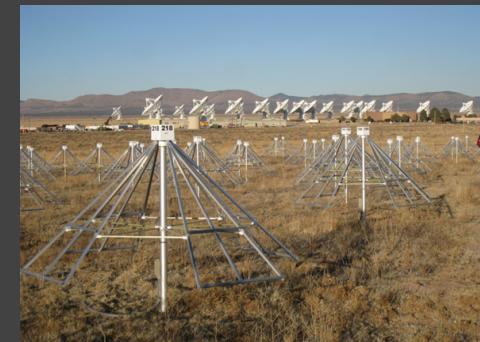
Lovell



Arecibo



LWA



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# Radio-X-ray campaigns on three radio-mode switching pulsars

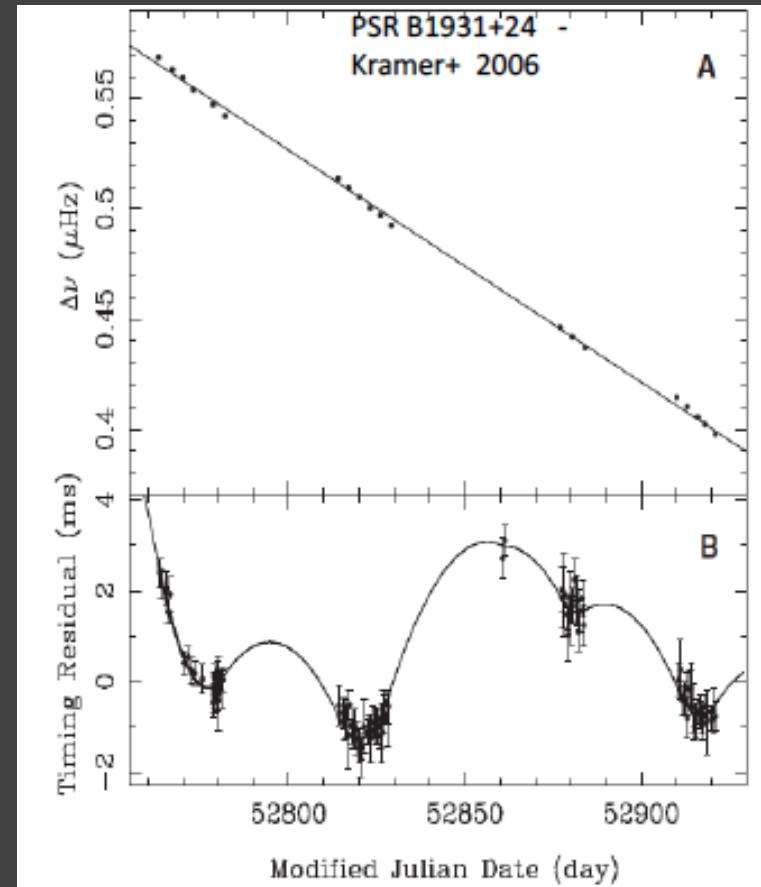
2011 - 2017

	PSR B0943+10	PSR B1822-09	PSR B0823+26
P [s]	1.10	0.77	0.53
P-dot	$3.5 \times 10^{-15}$	$5.2 \times 10^{-14}$	$1.7 \times 10^{-15}$
E-dot [erg s <sup>-1</sup> ]	$1.0 \times 10^{32}$	$4.5 \times 10^{33}$	$4.5 \times 10^{32}$
B <sub>p</sub> [G]	$2.0 \times 10^{12}$	$6.4 \times 10^{12}$	$9.6 \times 10^{11}$
Characteristic age [yr]	$5.0 \times 10^6$	$2.3 \times 10^5$	$4.9 \times 10^6$
B field / rotation axis	'aligned'	'orthogonal'	'orthogonal'

# Radio-mode switching a local or global phenomenon ?

**Observational Evidence** for Rapid, Global, Magnetospheric Changes:

- Mode switching and correlated  $\dot{\nu}$  changes for PSR B1931+2421  
(Kramer et al. 2006, Science 312, 549)



# Radio-mode switching a local or global phenomenon ?

## Observational Evidence for Rapid, Global, Magnetospheric Changes:

- Mode switching and correlated  $\dot{v}$  changes for PSR B1931+2421  
(Kramer et al. 2006, Science 312, 549)
- Mode changing, nulling, profile-shape changes likely due to change in magnetospheric particle current flow (Lyne et al. 2010, Science 329, 408)
- Similar behaviour for PSR J1841-0500 and J1832+0029  
(Camilo et al. 2012; Lorimer et al. 2012)
- Two more long-term intermittent pulsars, PSRs J1910+0517, J1929+1357, with PSR J1929+1357 showing  $v \propto$  proportional to duty cycle (Lyne et al. 2017, Ap.J. 834, 72)
- **Theoretical discussions on global quasi-stable magnetospheric states**  
(e.g. Goodwin et al. 2004, Timokhin 2006, 2010, Kalapotharakos et al. 2012, Li et al. 2012, Melrose & Yuen 2014, Jones 2018)

# Radio-mode switching a local or global phenomenon ?

Local phenomenon, Inner Acceleration Region:

- Three modes of pulsar inner gap (Zhang et al. 1997)
- Partially Screened Gap model (Gil, Melikidze, Zhang, 2006; Szary, Melikidze, Gil, 2015)

Accretion:

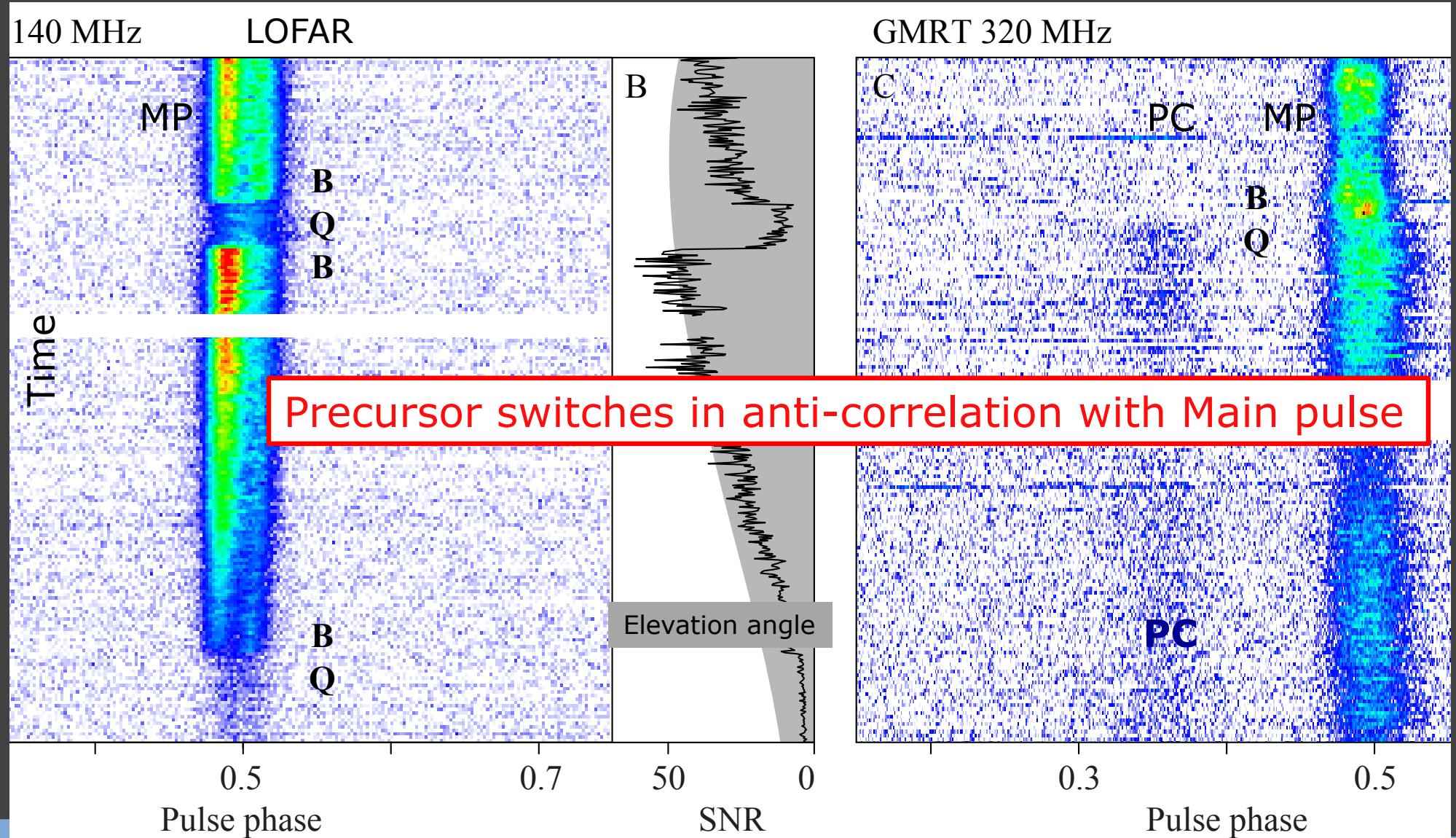
- Interstellar medium
- Fallback debris

(Wright 1979, Tsygan 1980, Cheng 1985, Luo & Melrose 2007, Cordes & Shannon 2008)

Can X-ray observations help?

# PSR B0943+10: radio-mode switching Main Pulse and Precursor mode durations typically hour(s)

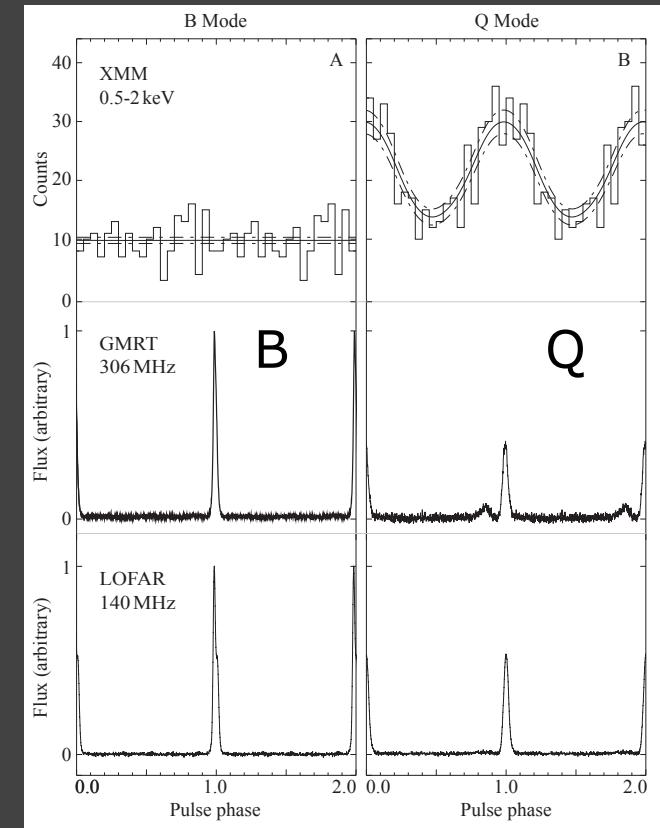
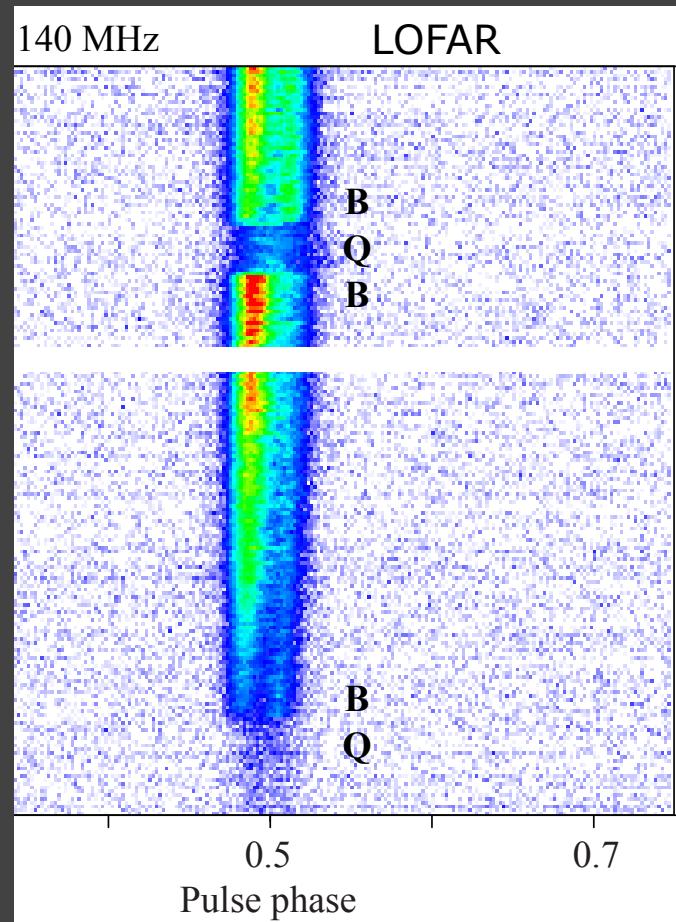
Hermsen et al. 2013



# Discovery of synchronous radio / X-ray mode switching

PSR B0943+10

Hermsen et al. 2013, Science 339, 436



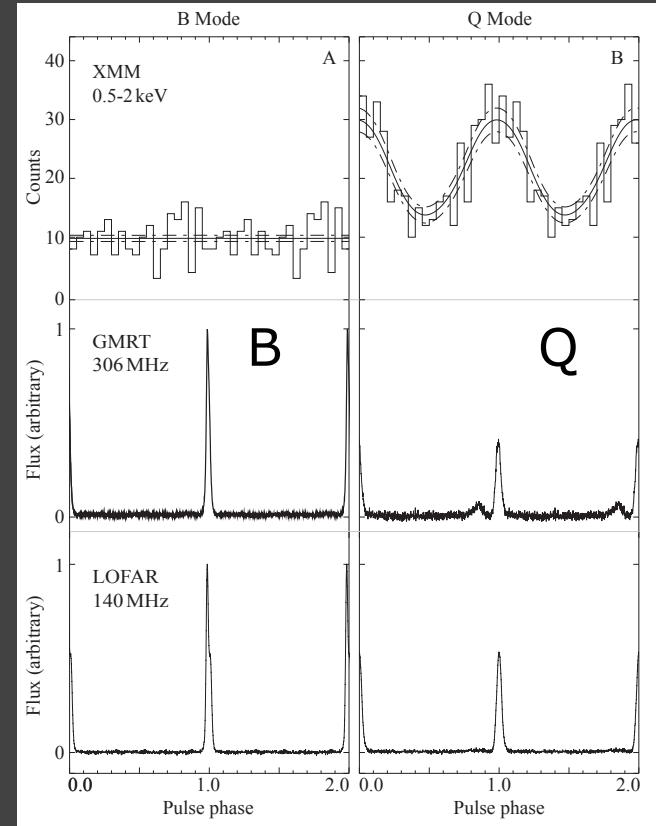
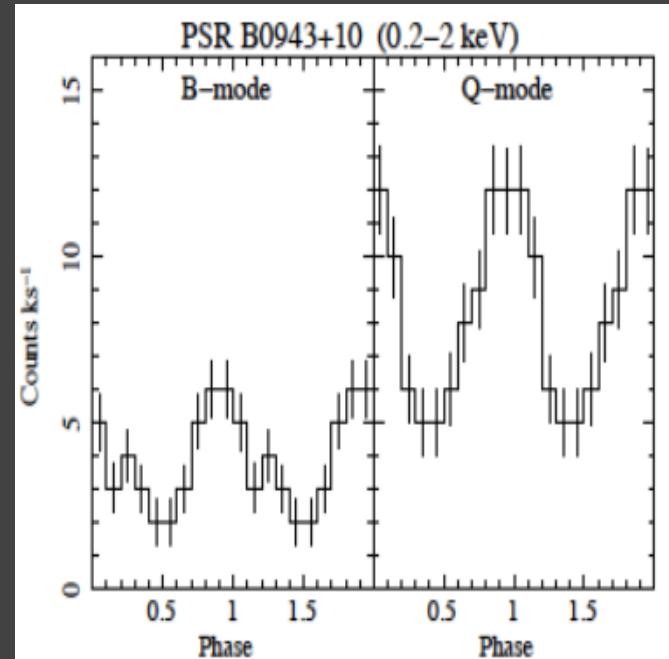
Anti-correlated radio and X-ray modulation!

Single X-ray pulse aligned with radio main pulse

# Discovery of synchronous radio / X-ray mode switching

Hermsen et al. 2013, Science 339, 436

Mereghetti et al. 2016, ApJ. 831, 21



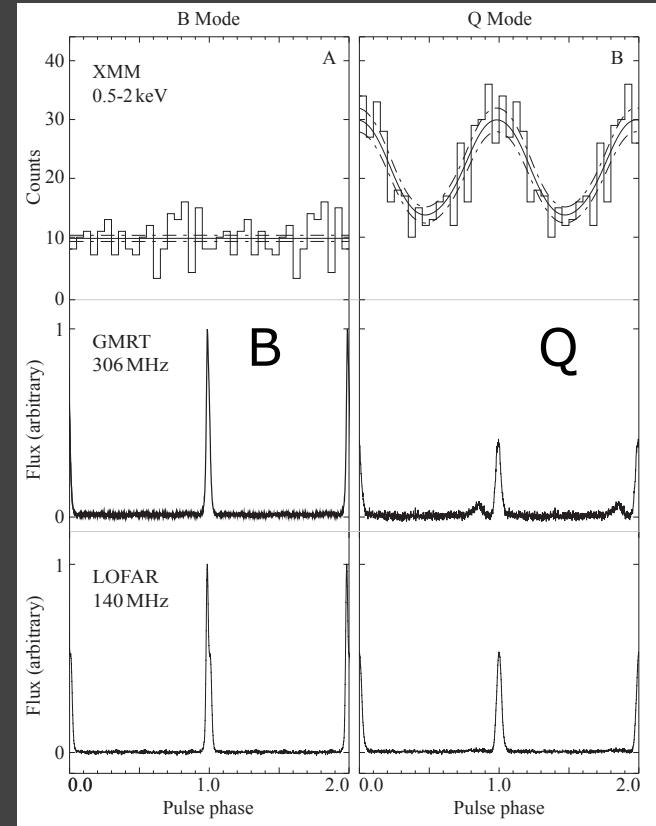
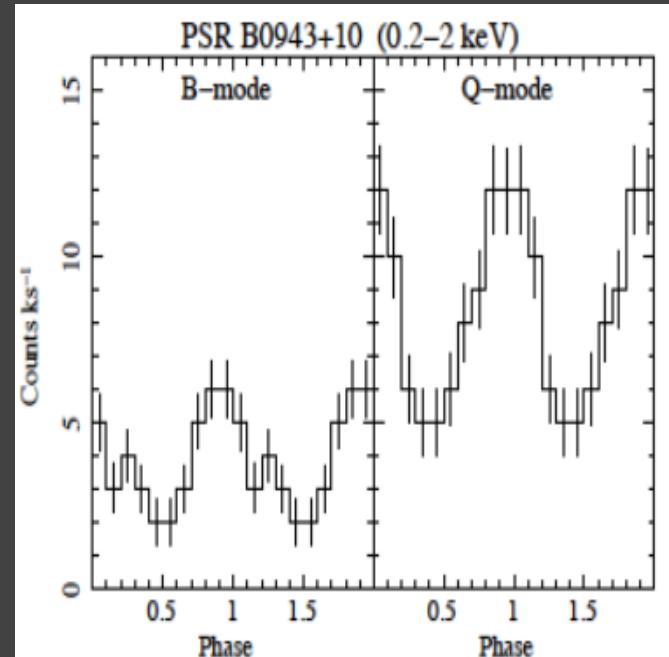
PSR B0943+10: near alignment

X-ray pulsed emission is thermal:  $kT \sim 3.4 \text{ MK}$ ,  $R_{\text{BB}} \sim 21 \text{ m}$   
X-ray unpulsed emission non-thermal: PL photon index  $\sim -2.5$

# Discovery of synchronous radio / X-ray mode switching

Hermsen et al. 2013, Science 339, 436

Mereghetti et al. 2016, ApJ. 831, 21



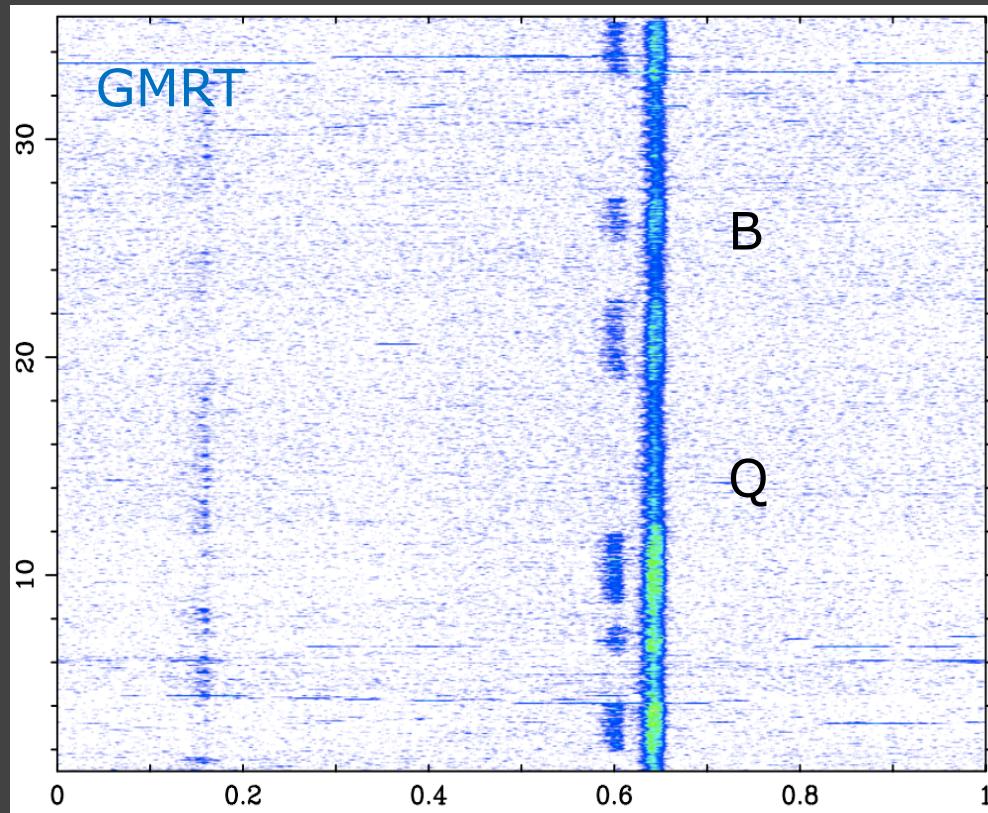
PSR B0943+10: near alignment

Magnetized hydrogen atmosphere model

Storch et al. 2014, Mereghetti et al. 2016, Rigoselli et al. 2019

# PSR B1822-09: radio modeing Precursor, Main and Interpulse mode durations typically minutes

Hermsen et al. 2017

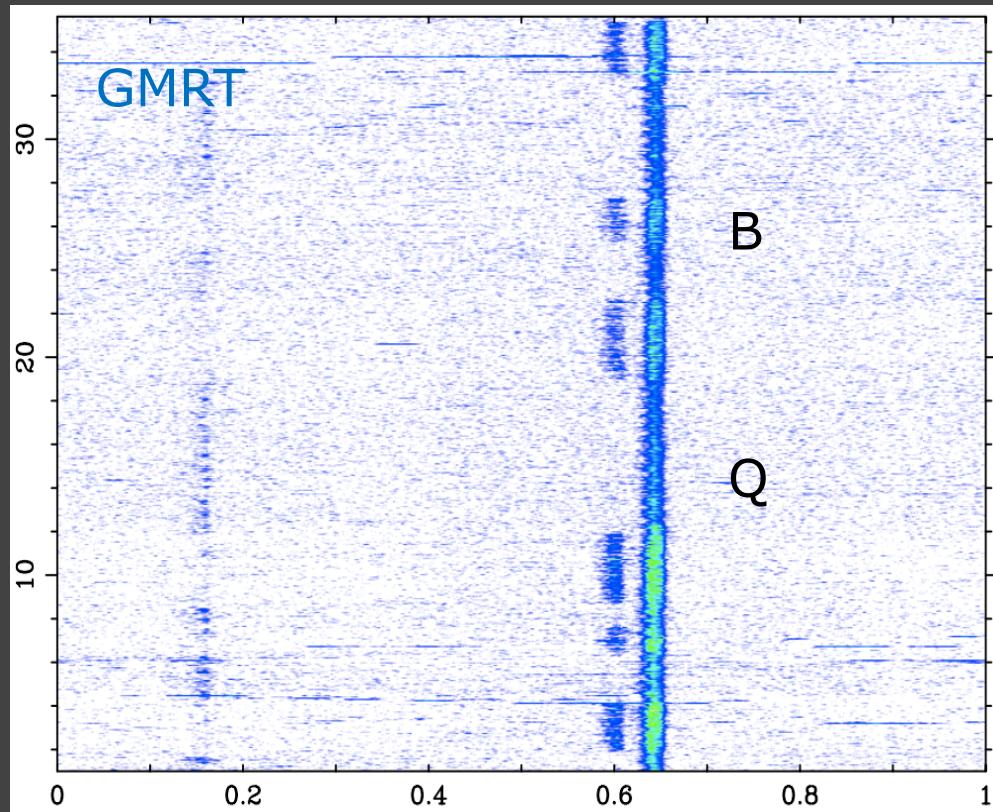


B  
Q

Precursor switches in correlation with Main pulse  
Interpulse switches in anti-correlation with Main pulse

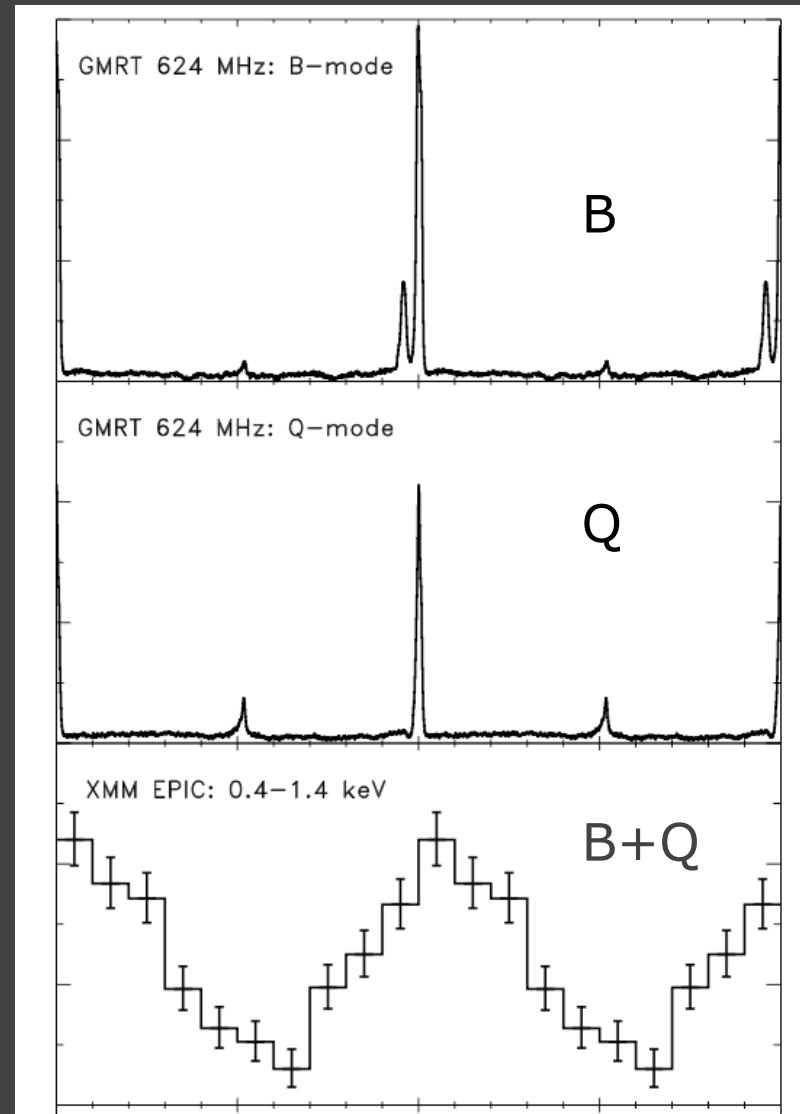
# PSR B1822-09: radio moding Precursor, Main and Interpulse mode durations typically minutes

Hermsen et al. 2017



NO X-ray mode changing

Single X-ray pulse lags radio pulse



PSR B1822-09: orthogonal rotator

# PSR B1822-09: radio moding Precursor, Main and Interpulse mode durations typically minutes

X-ray total emission is thermal:

$$kT_1 \sim 1.0 \text{ MK} \quad R_{\text{BB}} \sim 2 \text{ km}$$

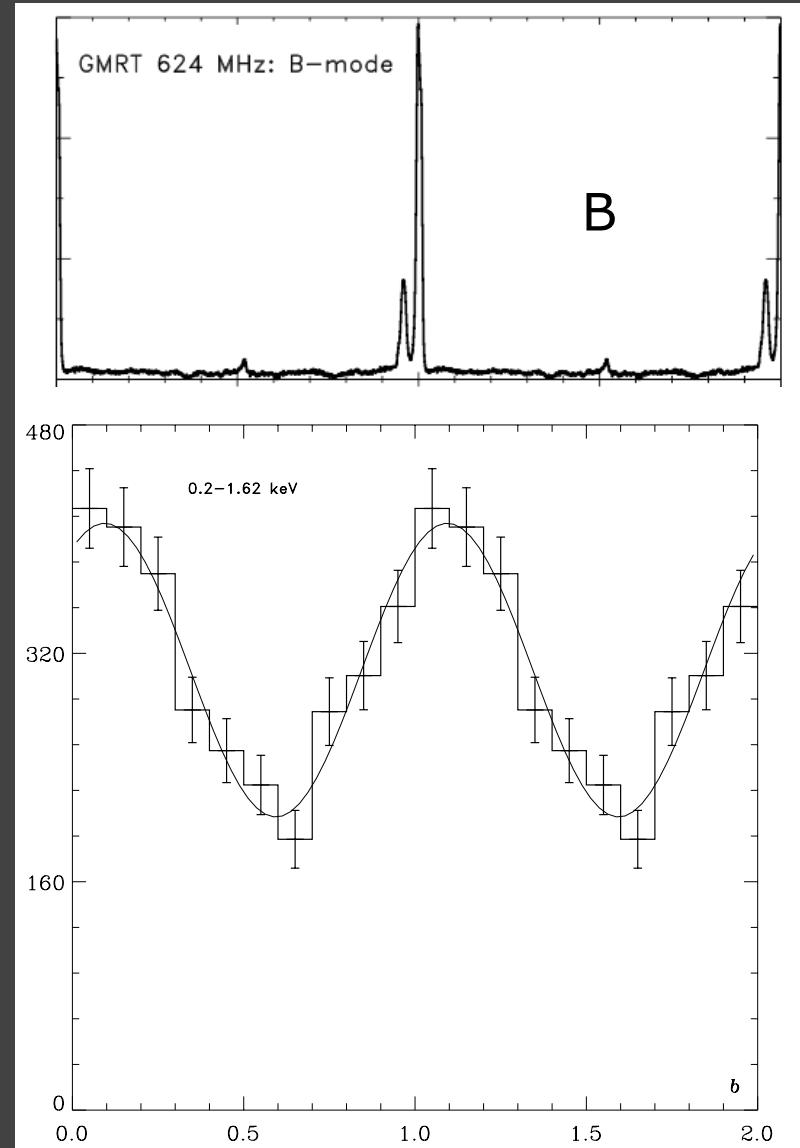
$$kT_2 \sim 2.2 \text{ MK} \quad R_{\text{BB}} \sim 100 \text{ m}$$

Hot component: pulsed emission

Cool component: from NS surface

High pulsed fraction  $\sim 60\% @ 1\text{keV}$ :

- One X-ray MP + one weaker X-ray IP
- Magnetic beaming involved ?

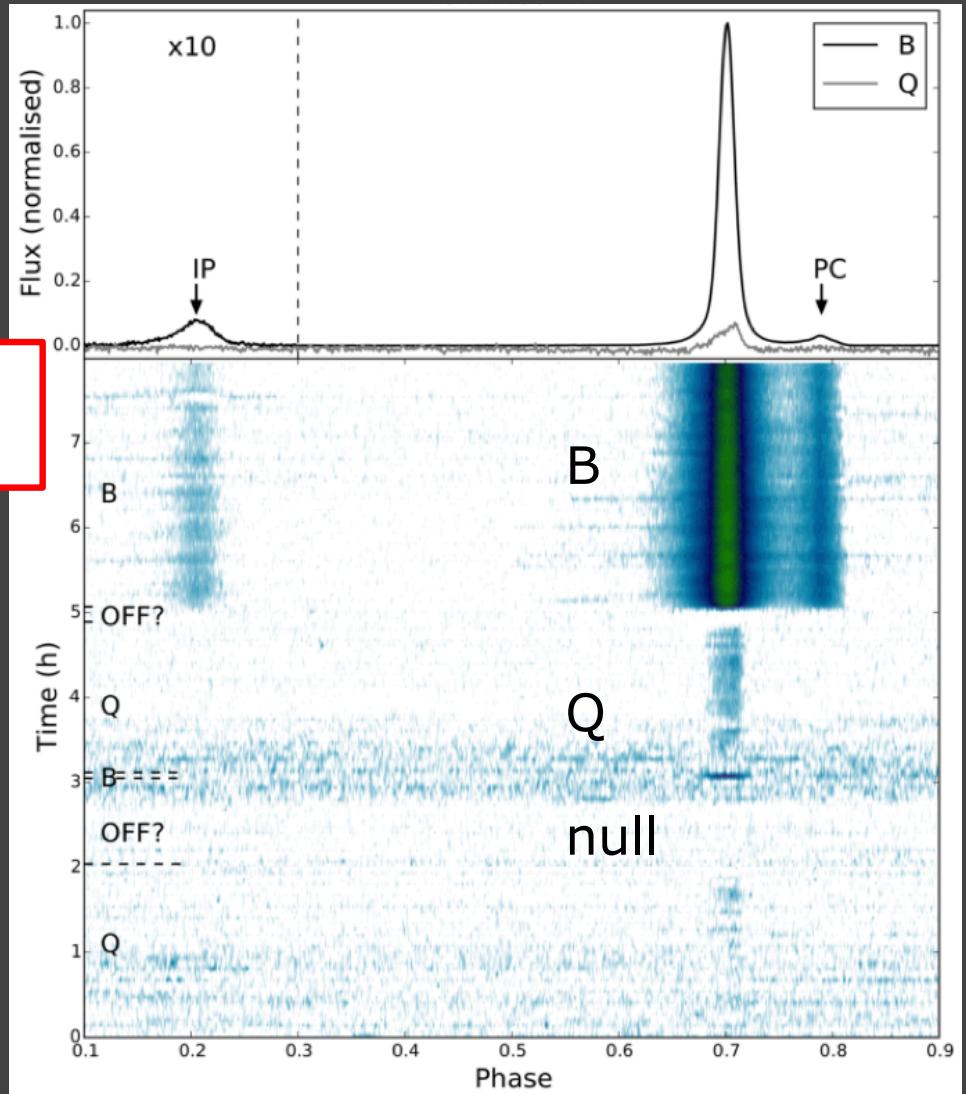


PSR B1822-09: orthogonal rotator

# **PSR B0823+26:** radio mode Postcursor, Main and Interpulse mode durations typically hours / days

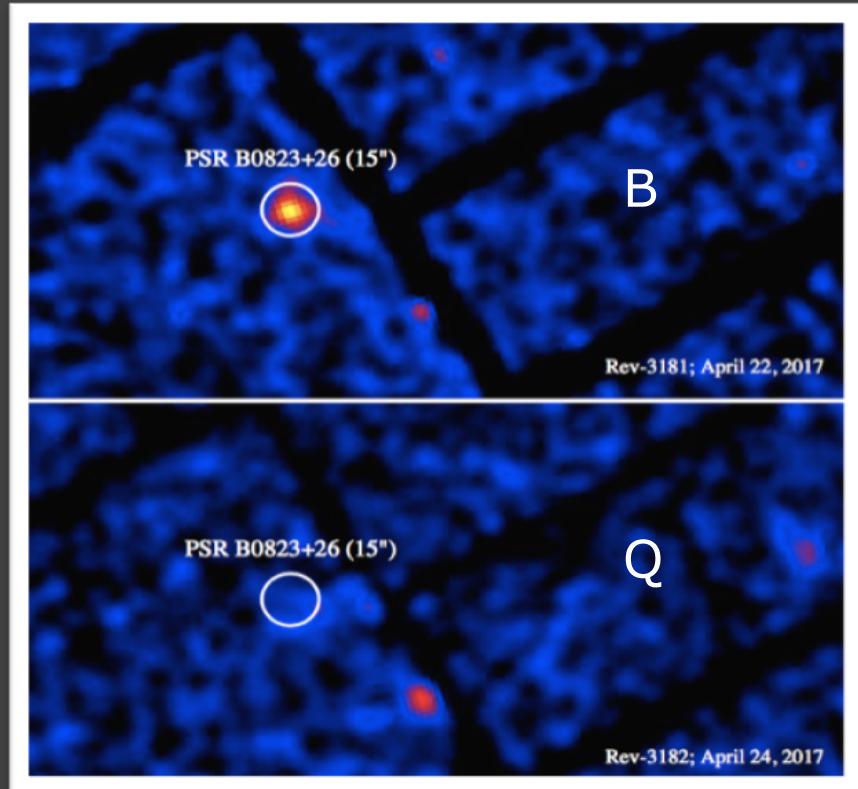
## Main pulse, Interpulse and Postcursor all show correlated switch

## Also OFF state: nulling

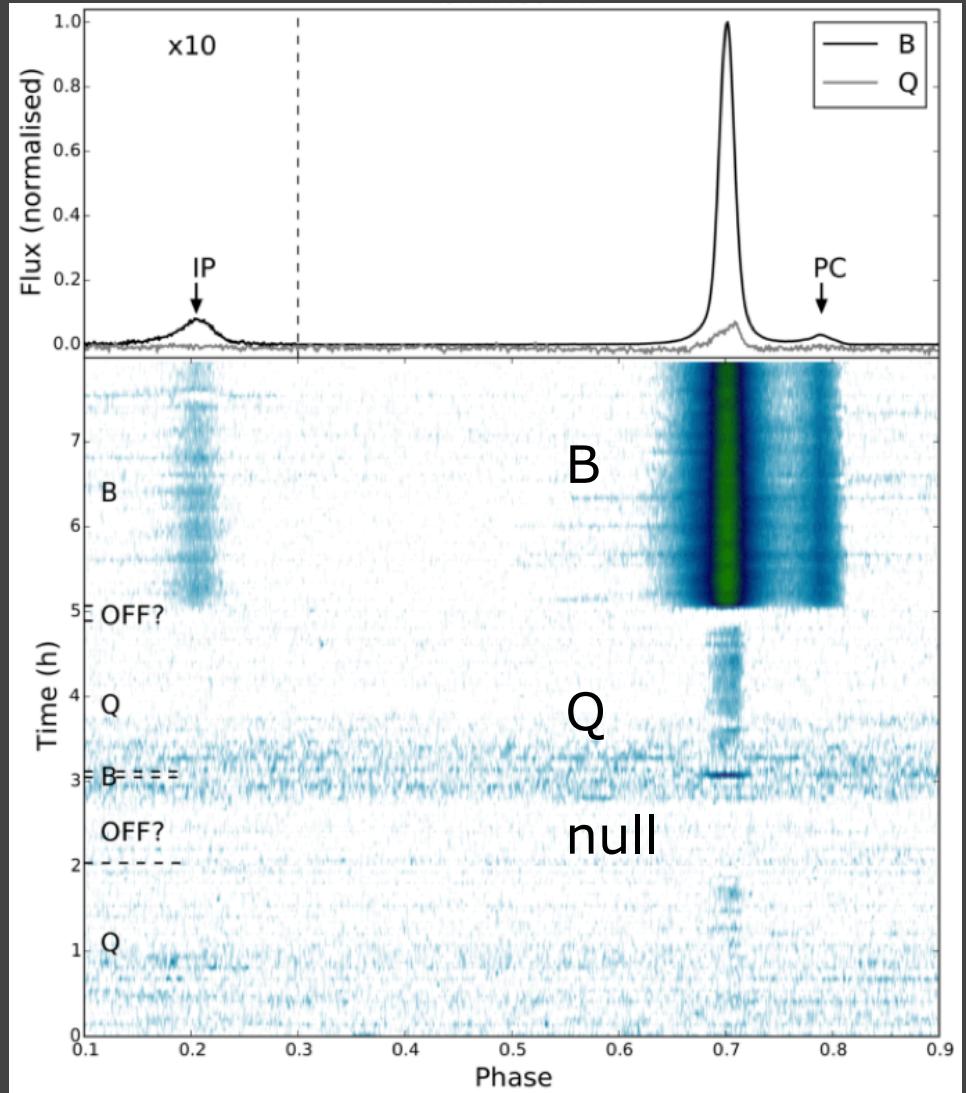


Sobey et al. 2015; LOFAR

# PSR B0823+26: radio moding Postcursor, Main and Interpulse mode durations typically hours / days

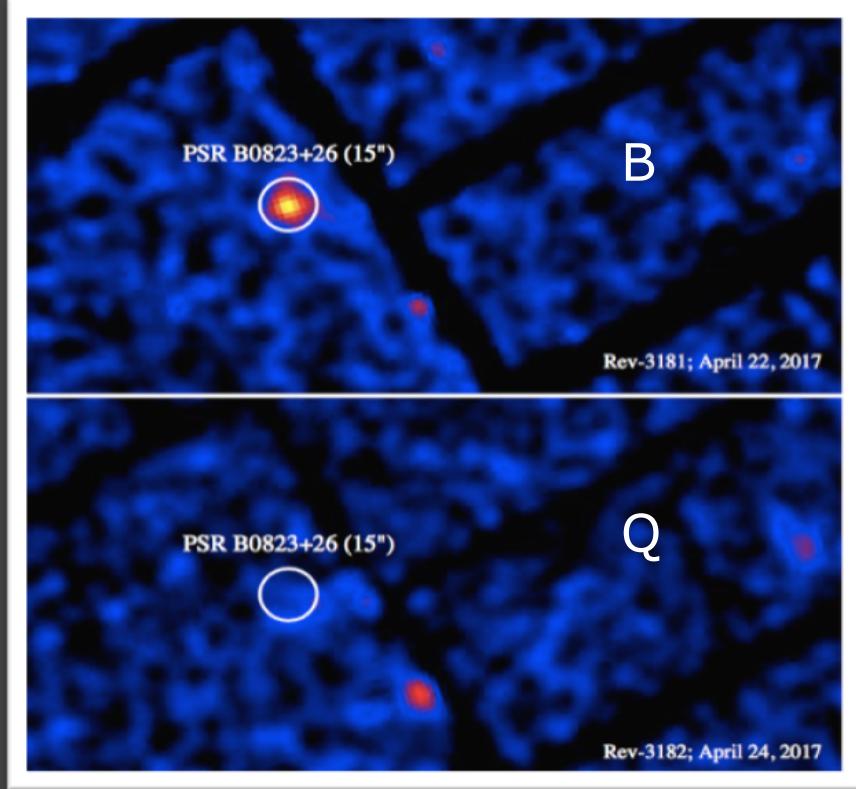


Correlated radio / X-ray moding!



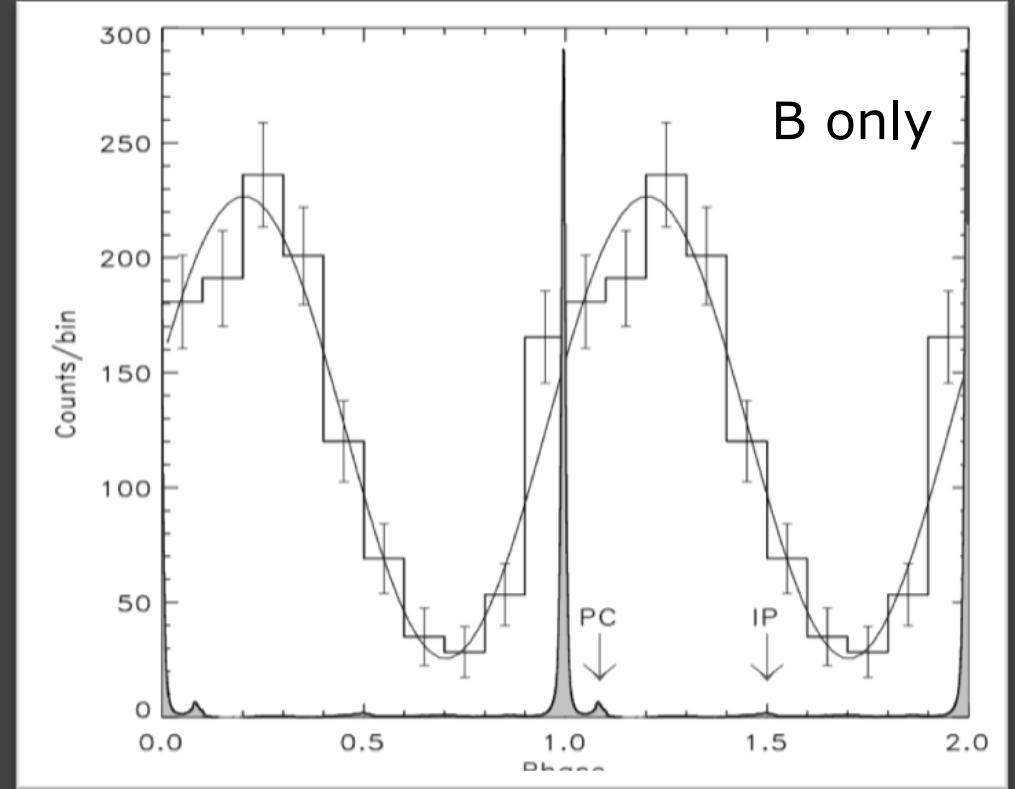
Sobey et al. 2015; LOFAR

# PSR B0823+26: radio moding Postcursor, Main and Interpulse mode durations typically hours / days



XMM-Newton

Near orthogonal rotator

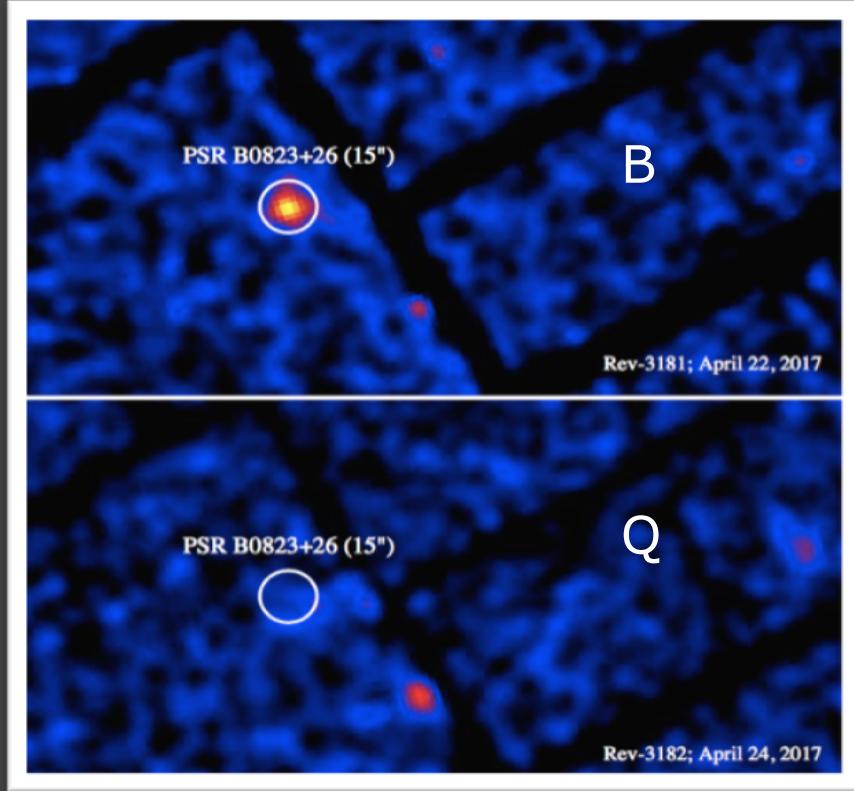


Single broad X-ray pulse

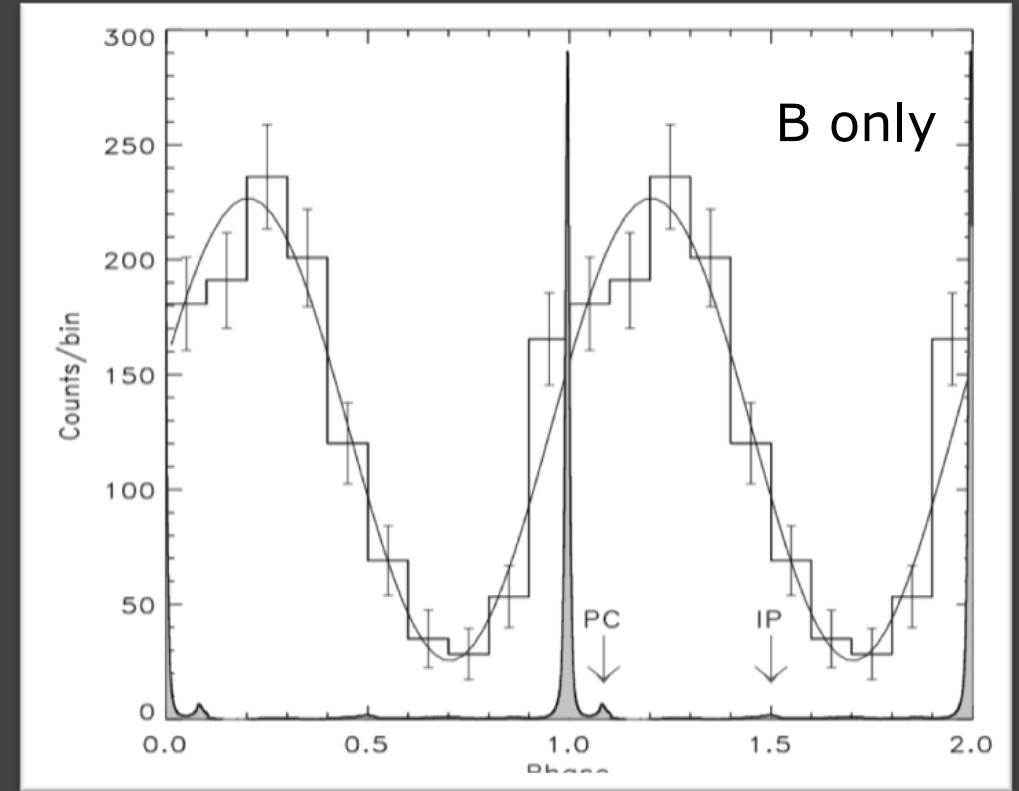
X-ray pulse lags radio pulse

Pulsed fraction very high ~80%

# PSR B0823+26: radio moding Postcursor, Main and Interpulse mode durations typically hours / days



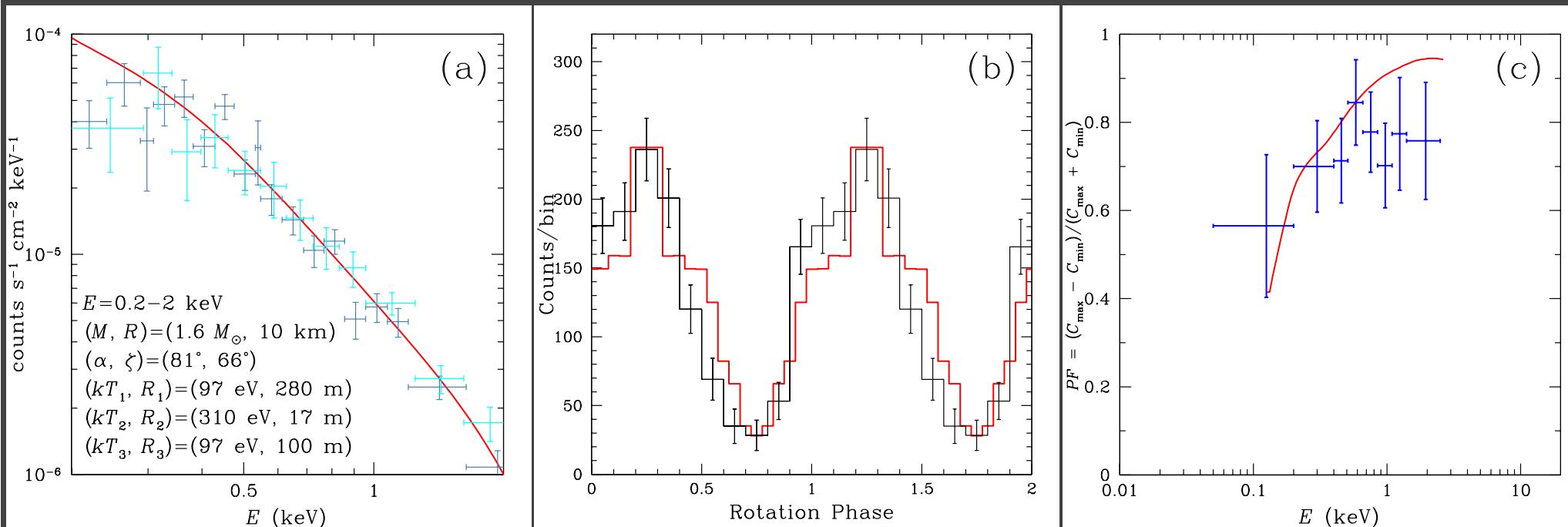
XMM-Newton



X-ray total and pulsed emissions thermal:  
 $kT_1 \sim 1.4 \text{ MK}$ ,  $R_{BB} \sim 77 \text{ m}$   
 $kT_2 \sim 4.3 \text{ MK}$ ,  $R_{BB} \sim 8.5 \text{ m}$

# PSR B0823+26: spectral analysis for B mode

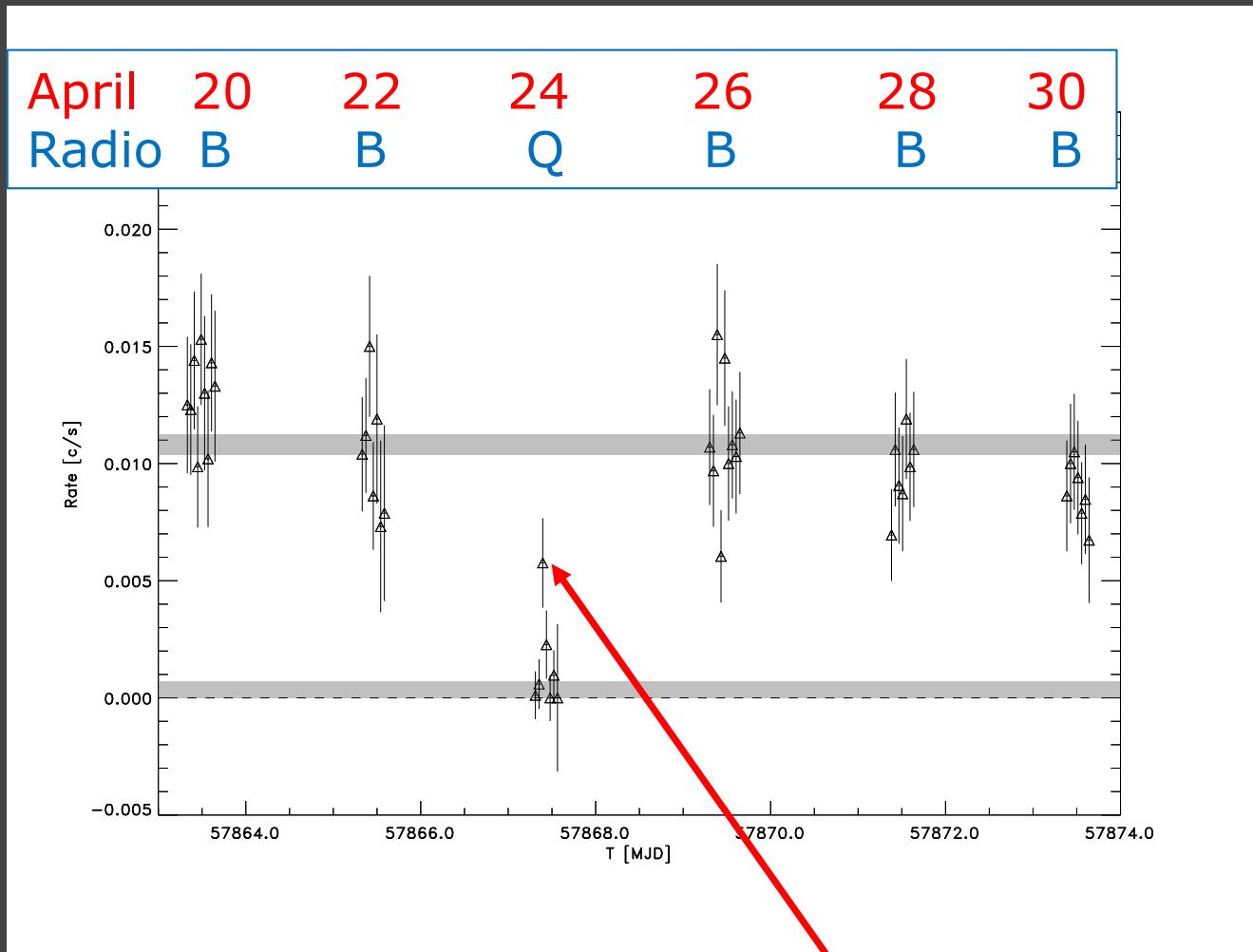
**Magnetized partially ionized hydrogen atmosphere model** Ho (2014)



Hermsen et al. 2018

However, angle between rotation axis and line-of-sight direction  $\sim 66^\circ$ , while radio-derived value is  $\sim 84^\circ$ : inconsistency?

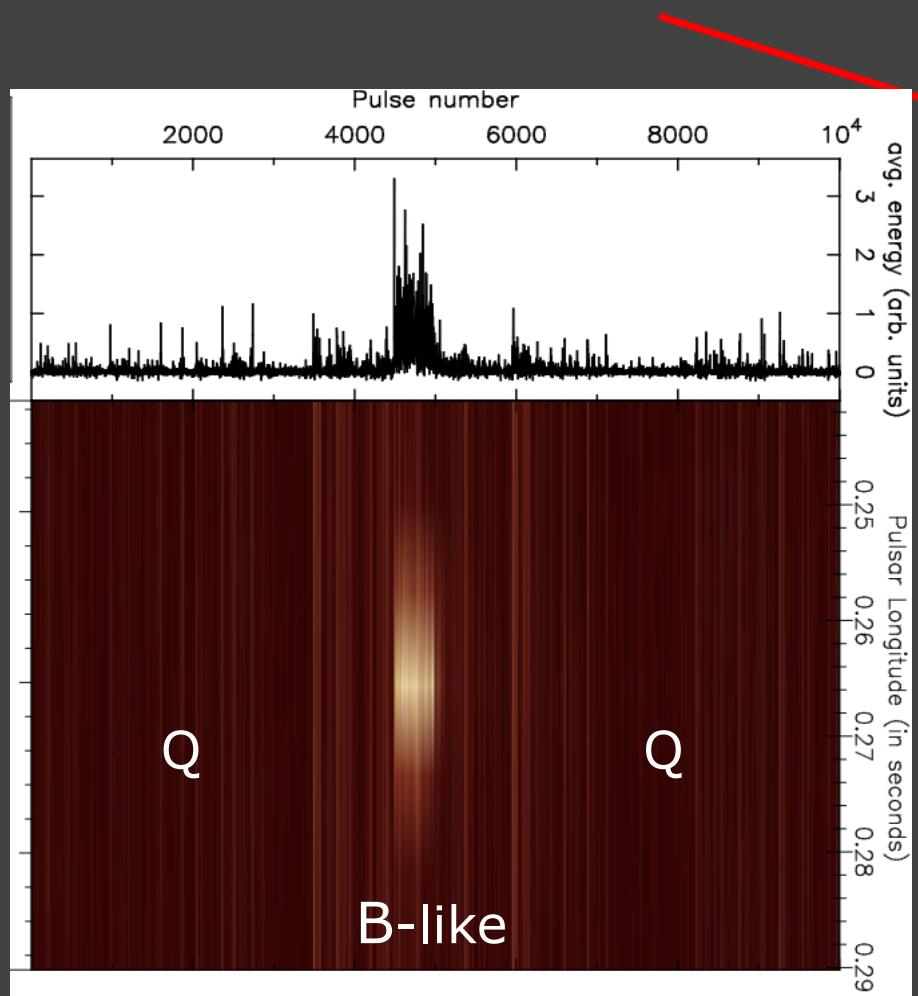
# PSR B0823+26: X-ray count rates 0.2-2 keV in $\sim$ 1 hr bins



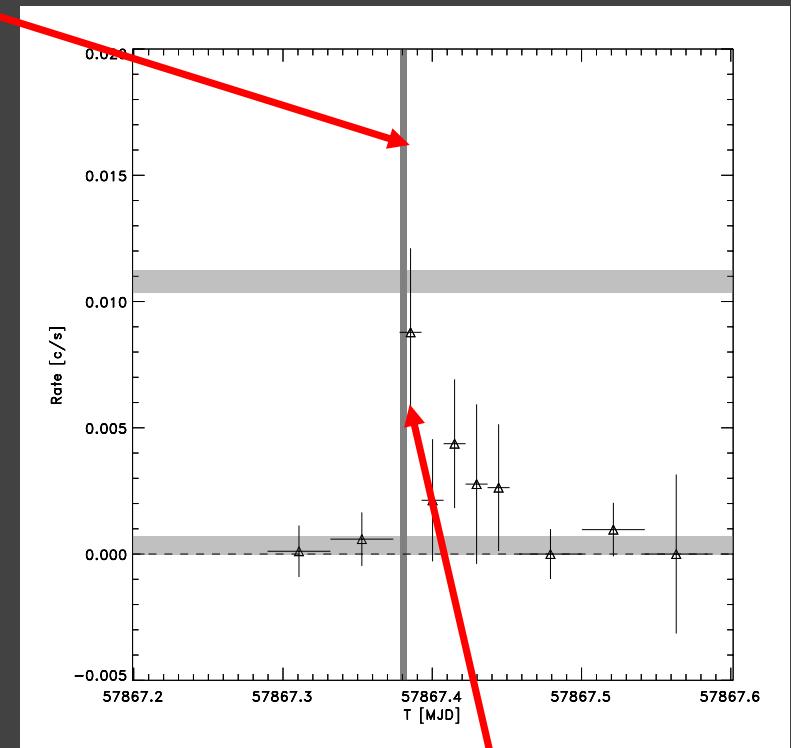
In skymap  $4.6 \sigma$ !

# PSR B0823+26

April 24, 7.5 hrs of Q-mode observations plus short  
~6 minutes 'B-like'.

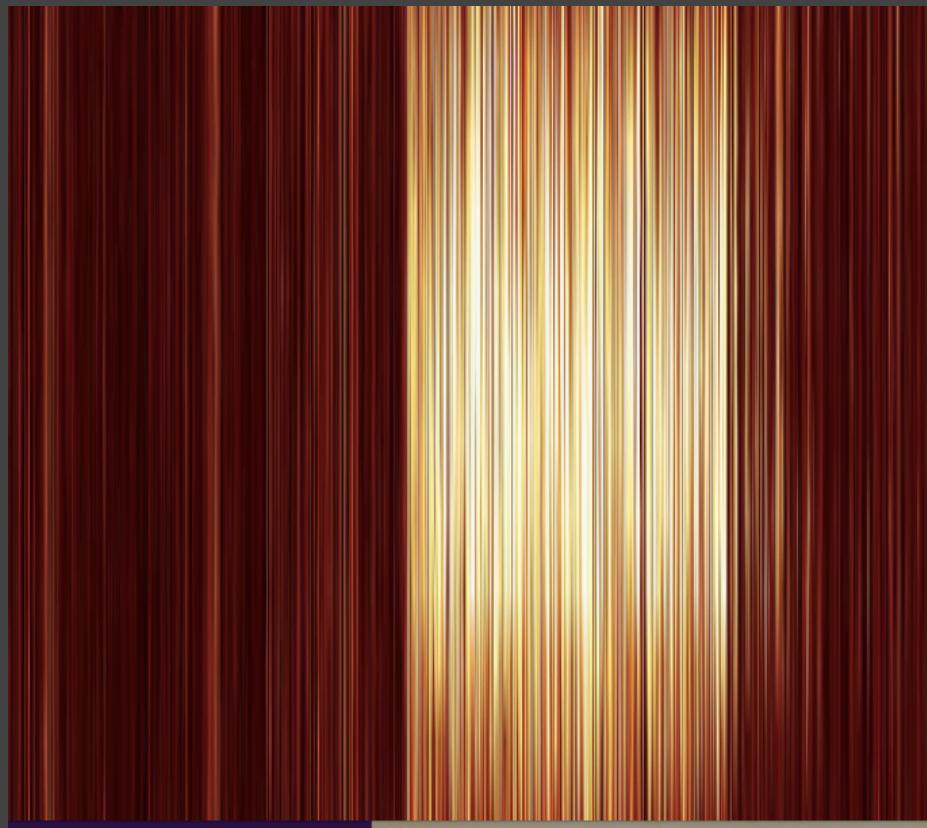


GMRT at 339.3 MHz

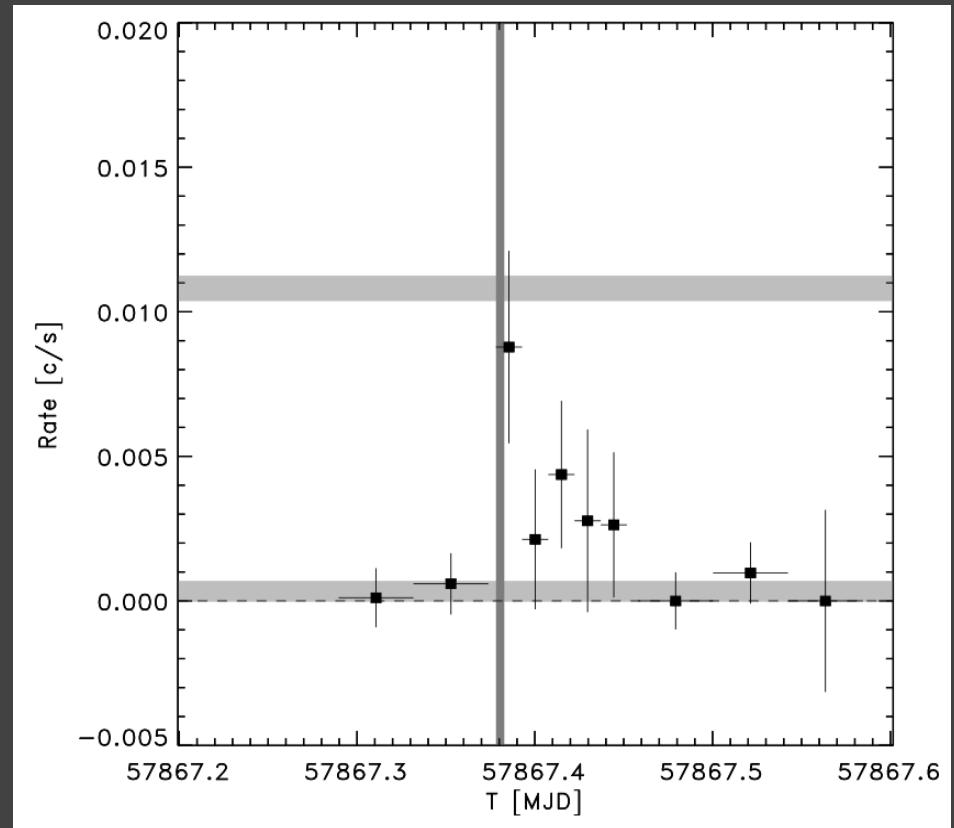


In skymap 4.5  $\sigma$       XMM  
in interval of 21 minutes

# PSR B1823+26 radio-burst structure



GMRT

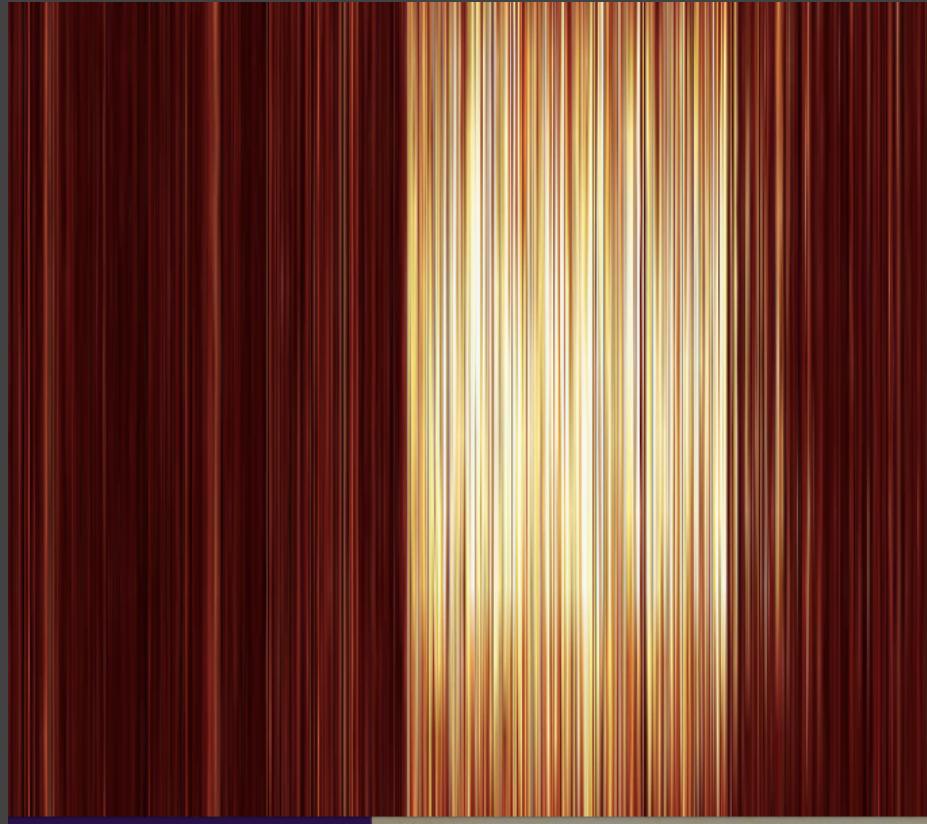


XMM

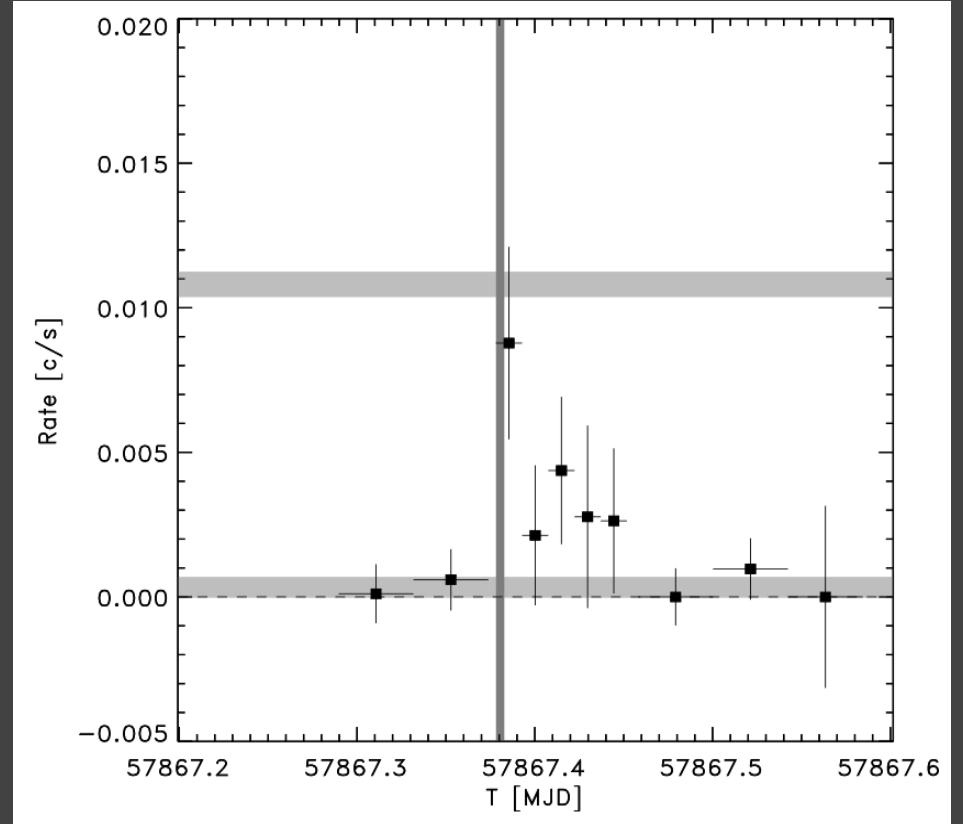
Q-to-B is sudden.....but B-to-Q is not

PSR B0943+10 & B1822-09 both transitions are sudden

# PSR B1823+26 radio-burst structure



GMRT

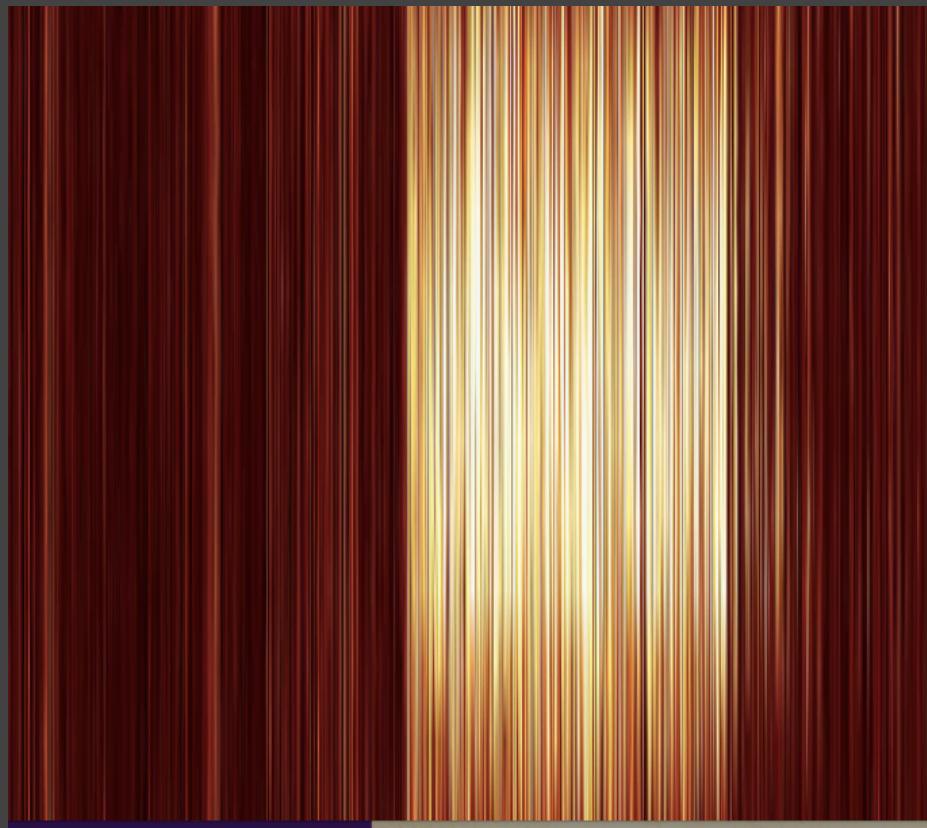


XMM

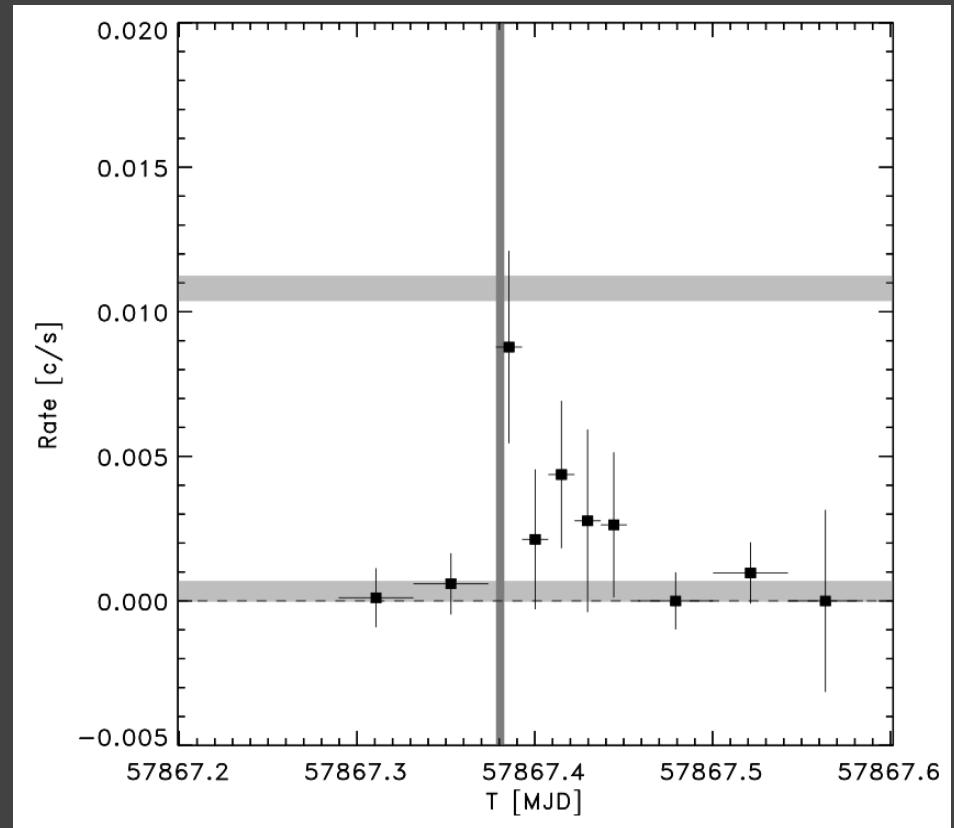
Q mode exhibits for >90% short nulls with occasional pulses/bursts  
B mode ~ 1-2% short nulls (Basu & Mitra 2019; Rankin & Olszanski)

PSR B0943+10 & B1822-09 do not show such short nulls

# PSR B1823+26 radio-burst structure



GMRT



XMM

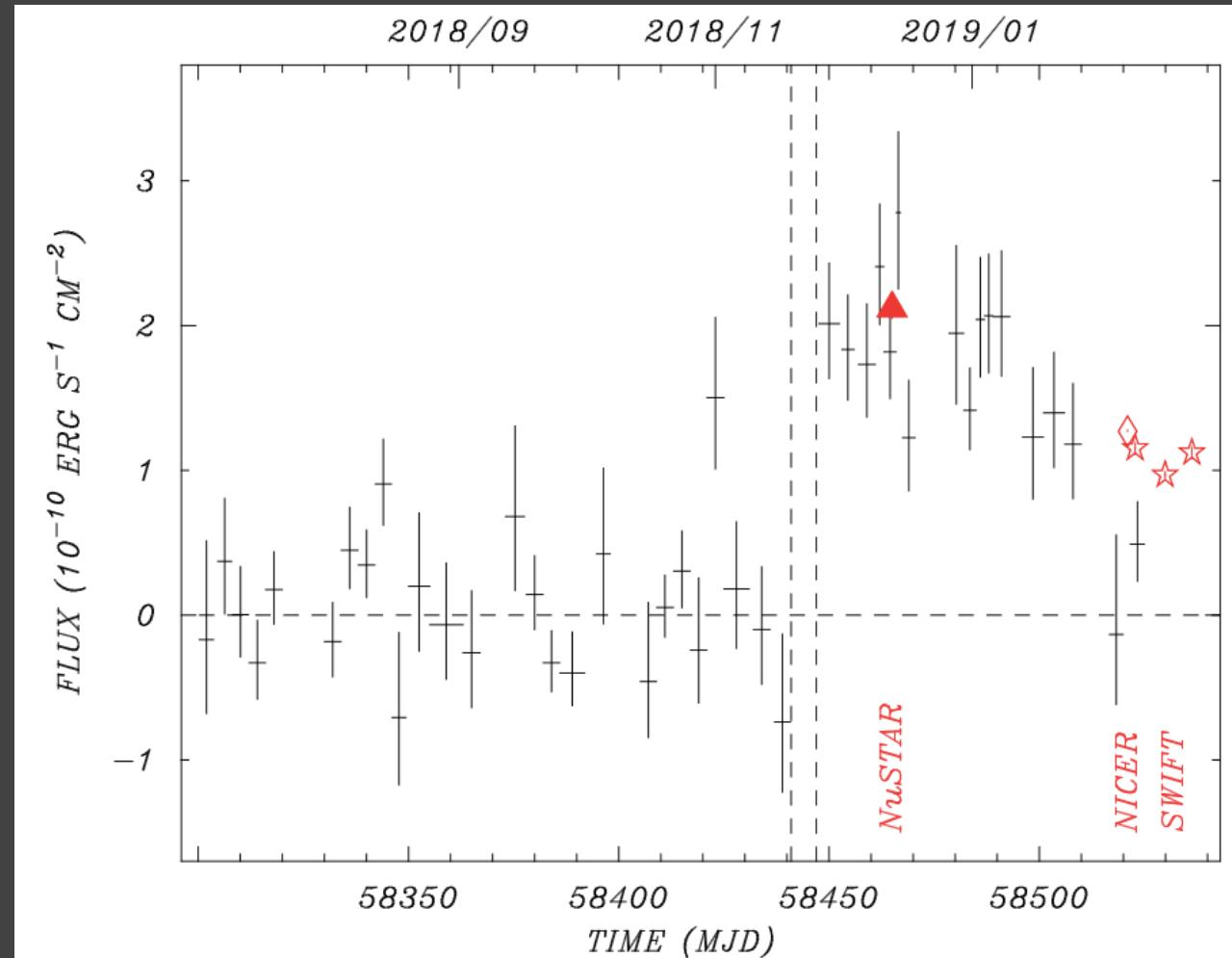
Sudden appearance of strong bursts, self-organized criticality?

Accretion from interstellar medium?

# A clue (Wright, Pharos meeting 2019): 'revived' magnetar XTE J1810-197

- Burst into activity December 2018
- Quiescent and Bright modes
- Sudden onset of burst in radio and X rays

Timescale: 10 years

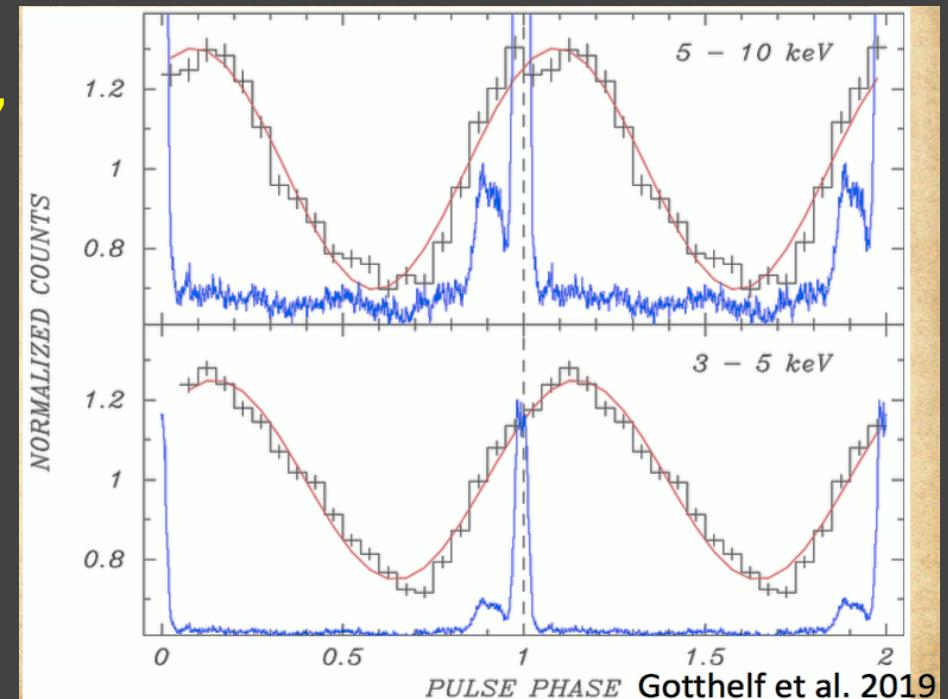


Gotthelf et al. 2019

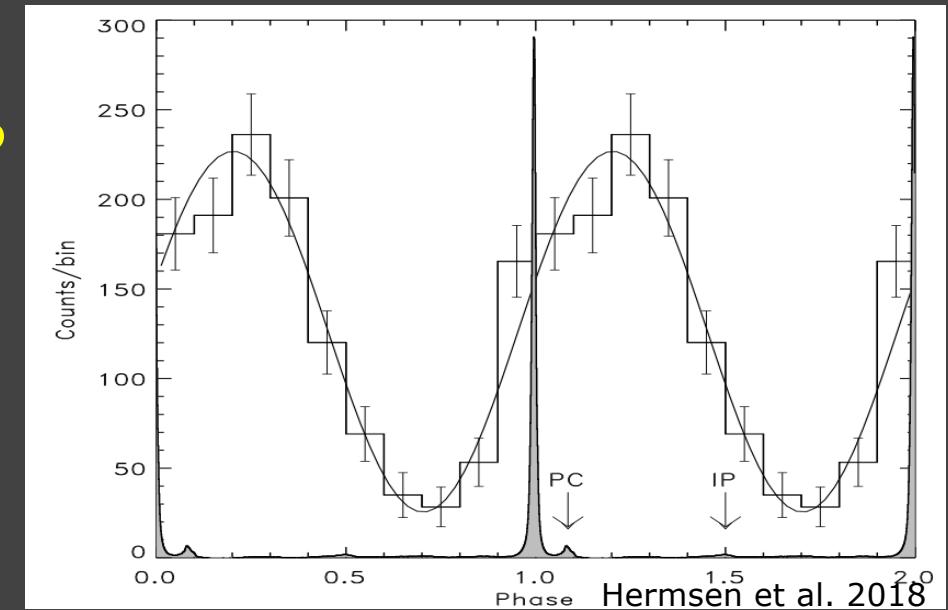
# Similar profiles

XTE J1810-197

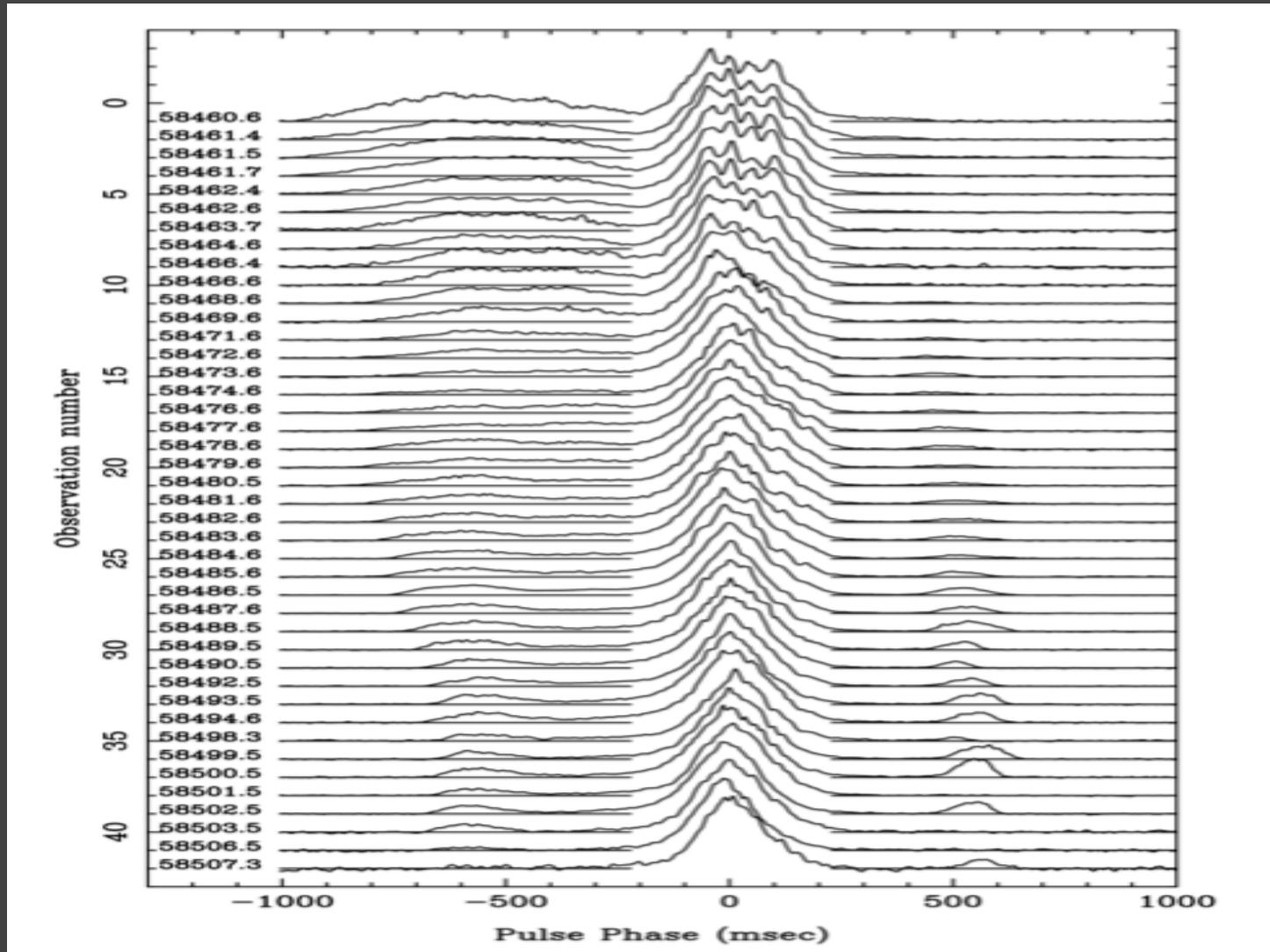
- Single-peak X-ray pulse
- X-peak follows radio peak
- Pre- and post-cursors



PSR B0823+26



# Post- and Pre-cursor of XTE J1810-197



Lovell  
1.52 GHz

Levin et al. 2019

- Precursor migrates to postcursor over 50 days!

# Same pattern on different timescales

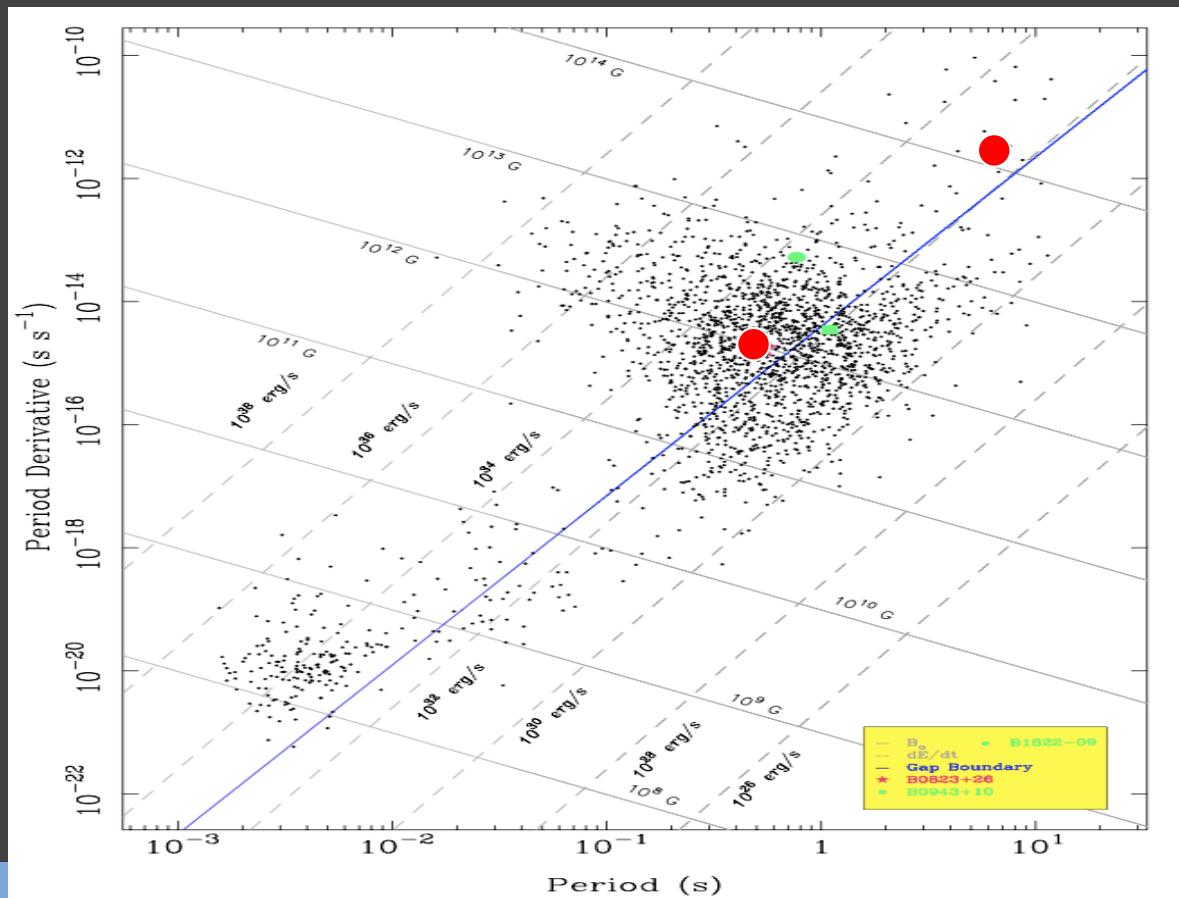
Pulsar P = 0.53 s

B  $\sim$  10<sup>12</sup> G

Magnetar P = 5.54 s

B  $\sim$  2x10<sup>14</sup> G

But spindown loss rate  $\sim 5 \times 10^{32}$  erg/s - same for both



# Summary

- PSR B0943+10, B1822-09 and B0823+26 exhibit very different radio (moding) characteristics
  - PSR B0943+10 shows anti-correlated X-ray / radio mode switching of a thermal pulse and a non-thermal unpulsed component.
  - PSR B1822-09 shows no X-ray mode switching
  - PSR B0823+26 shows correlated X-ray / radio mode switching with a two-temperatures thermal pulse
- Simultaneous X-ray and radio mode switching: Local and/or magnetospheric phenomenon?



Thank you for listening!